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THE IMPACT OF COOLING AND PREHEATING ON THE SUNYAEV-ZELDOVICH EFFECT

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ABSTRACT

We use hydrodynamical simulations to assess the impact of radiative cooling and “preheating” on predictions for the Sunyaev-Zeldovich (SZ) effect. Cooling significantly reduces both the mean SZ signal and its angular power spectrum, while preheating can increase the mean distortion while leaving the angular power spectrum below that found in a simulation without heating or cooling. We study the relative contribution from high- and low-density gas, and we find that in the cooling model about 60% of the mean thermal distortion arises from low-overdensity gas. We find that halos dominate the thermal SZ power spectrum in all models, while in the cooling simulation the kinetic SZ power spectrum originates predominantly in lower overdensity gas.

Subject headings: cosmic microwave background — cosmology: theory — galaxies: clusters: general — methods: numerical

1. INTRODUCTION

One of the most promising techniques for detecting overdense structures at high redshift is from their imprint on the cosmic microwave background (CMB), known as the Sunyaev-Zeldovich (SZ) effect (Sunyaev & Zeldovich 1972, 1980). The SZ effect arises owing to scattering of the CMB photons from electrons in regions of ionized gas. It has two components, the thermal and kinetic effects (see Birkinshaw 1999 for a review). Successful SZ detections toward known low-redshift galaxy clusters are now routine (e.g., Jones et al. 1993; Myers et al. 1997; Carlstrom et al. 2000), and observational studies are poised to move to blank field surveys of the sky in an attempt to discover their high-redshift counterparts (e.g., Lo et al. 2000; Kneissl et al. 2001). This has led to an upsurge in theoretical work predicting what future surveys might see, the most powerful technique being the use of N -body/hydrodynamical simulations to make high-resolution maps (da Silva et al. 2000, 2001; Refregier et al. 2000; Seljak, Burwell, & Pen 2001; Springel, White, & Hernquist 2001). While these simulations model gravitational collapse, adiabatic compression, and shock heating of the baryons, they ignore the effects of radiative cooling, which affects the thermal state of the gas, particularly in halos (Pearce et al. 2000; Muanwong et al. 2001) where the SZ signal is strongest. In addition, it is now believed that the baryons were subjected to nongravitational heating processes, probably before clusters formed (e.g., Ponman, Cannon, & Navarro 1999); such preheating could come from the feedback of energy from supernovae or active galactic nuclei and is therefore inherently related to the galaxy formation process.

In this Letter we present a first attempt to simulate the SZ effect using hydrodynamical simulations that implement models for both radiative cooling and preheating. While these simulations cannot be regarded as definitive, they illustrate how these processes affect predictions for SZ-related quantities. We focus on the simplest measurable quantities, which are the mean thermal distortion and the dispersion and angular power spectra

of the SZ-induced temperature anisotropies. We also quantify the relative contributions to the SZ effect from bound gas in halos and low-overdensity intergalactic medium (IGM).

2. SIMULATION DETAILS AND SZ MAPMAKING

We present results from three simulations of the currently favored Λ cold dark matter (CDM) cosmology. We set the cosmological parameters as follows: matter density, $\Omega_m = 0.35$; cosmological constant, $\Omega_\Lambda \equiv \Lambda/3H_0^2 = 0.65$; Hubble constant, $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1} = 0.71$; baryon density, $\Omega_b h^2 = 0.019$; and normalization, $\sigma_8 = 0.9$. The density field was constructed using $N = 4,096,000$ particles of both baryonic and dark matter, perturbed from a regular grid of fixed comoving size $L = 100 h^{-1} \text{ Mpc}$. The dark matter and baryon particle masses are 2.1×10^{10} and $2.6 \times 10^9 h^{-1} M_\odot$, respectively. In physical units, the gravitational softening was held fixed to $25 h^{-1} \text{ kpc}$ below $z = 1$ and above this redshift scaled as $50(1+z)^{-1} h^{-1} \text{ kpc}$. Each simulation took approximately 2300 time steps to evolve to $z = 0$, using a parallel version of the Hydra code (Couchman, Thomas, & Pearce 1995; Pearce & Couchman 1997), which uses the adaptive particle-particle/particle-mesh (AP³M) algorithm to calculate gravitational forces (Couchman 1991) and smoothed particle hydrodynamics (SPH) to estimate hydrodynamical quantities. Our SPH implementation follows that used by Thacker & Couchman (2000), where more details can be found.

The first of the three simulations was performed without any additional heating or cooling mechanisms; we refer to this as the “nonradiative” simulation. The second simulation included a model for radiative cooling using the method described in Thomas & Couchman (1992), except that we adopted the cooling tables of Sutherland & Dopita (1993) and a global gas metallicity evolving as $Z = 0.3(t/t_0) Z_\odot$, where $t_0 \approx 12.8 \text{ Gyr}$ is the current age of the universe. Cooled gas is converted into collisionless material and no longer participates in generating the SZ effect. This fraction is negligible at $z = 6.5$ (the highest redshift we consider in computing the SZ effect) but increases to $\sim 20\%$ by the present. Although this model provides acceptable matches to the $z = 0$ X-ray group/cluster scaling relations (Muanwong et al. 2001), the fraction of cooled material is uncomfortably high when compared to observational determinations (e.g., Balogh et al. 2001). Hence, this simulation provides an extreme case in terms of the amount of cooling obtained.

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Our third simulation, which also includes cooling, was performed in order to study the effects of preheating the gas at high redshift. Although attempts are now being made to include effective energy feedback from supernovae within cosmological simulations (e.g., Kay et al. 2001), the modeling can be done only at a phenomenological level since the true physical processes occur on much smaller scales than are resolved. For the purposes of this Letter, we adopt a particularly simple model, which is to take the output from the radiative simulation at $z = 4$ and raise the specific thermal energy of all gas particles by 0.1 keV (an equivalent temperature of 1.2×10^6 K) before evolving to $z = 0$ as before. This choice of energy is motivated by observations of an “entropy floor” in X-ray groups by Lloyd-Davies, Ponman, & Cannon (2000); we define specific “entropy” as $s = k_B T/n^{2/3}$, and our injection model would give $s_{\text{floor}} \sim 80 \text{ keV cm}^2$ were the gas all at mean density. This reduces the amount of cooled material to a more acceptable level ($\sim 10\%$), although a greater amount of heating would have been needed to give the best match to the X-ray scaling relations.

These simulations have two advantages over those we studied previously (da Silva et al. 2000, 2001). First, those simulations did not include radiative cooling and so contain hot, high-density gas where the cooling time is much shorter than a Hubble time. Second, the new simulations have improved numerical resolution (the particle masses are a factor of 19 smaller), allowing the SZ effect to be studied at smaller scales.

We analyze the SZ effect by constructing simulated SZ maps⁵ of area 1 deg^2 , stacking simulation boxes from low to high redshift (up to redshift $z \sim 6.5$) as described by da Silva et al. (2000). The vast majority of the thermal SZ signal is produced well within this redshift interval. We repeat this process to produce 30 random map realizations for each run, using the same sequence of random seeds for the different models. The thermal effect is described by the Comptonization parameter y , and the kinetic by the temperature perturbation $\Delta T/T$.

3. RESULTS

The mean y distortion, obtained by averaging y over lines of sight, is an important measure of the global state of the gas in the universe. In our simulations we find the following:

$$\text{nonradiative : } y_{\text{mean}} = 3.2 \times 10^{-6},$$

$$\text{cooling : } y_{\text{mean}} = 2.3 \times 10^{-6},$$

$$\text{preheating : } y_{\text{mean}} = 4.6 \times 10^{-6}.$$

(For comparison, the mean mass-weighted temperatures at $z = 0$ in the three simulations are 0.39, 0.35, and 0.38 keV.) At present, the best upper limit is $y_{\text{mean}} < 1.5 \times 10^{-5}$ from COBE/FIRAS (Fixsen et al. 1996), and all our models are well below this. The cooling simulation gives the lowest level of distortion, and the preheating gives the highest. The factor of 2 difference between these runs shows that the mean y is quite sensitive to preheating. The mean y distortion in the nonradiative model is slightly smaller than the value found in da Silva et al. (2000); part of this difference is attributable to a different σ_8 , and the remainder lies within the uncertainty expected from changes to the simulation technique.

To study the relative contribution to the SZ effect from the different gas phases in the simulations, we sorted the particles

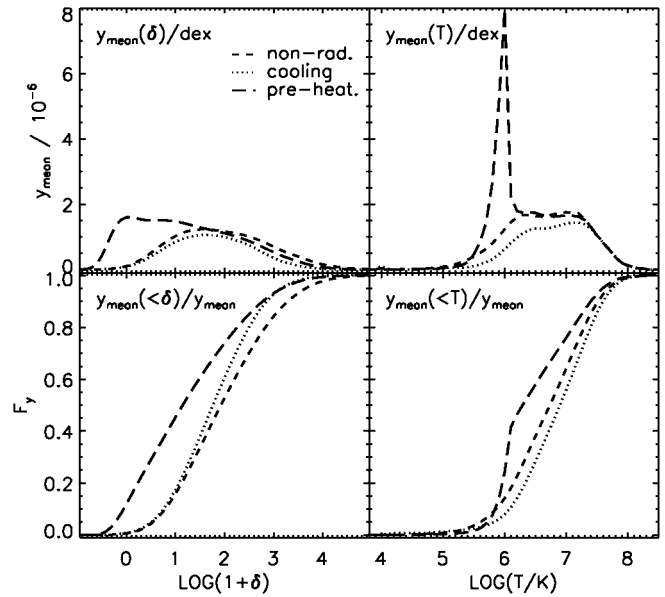


FIG. 1.—Fractional contribution to y_{mean} as a function of temperature and overdensity. *Top panels*: the contribution for a unit interval (in base-10 logarithm); *bottom panels*: the integrated contribution.

in each simulation according to their temperature, T , and overdensity, δ , and computed the fraction of SZ signal arising from all particles at a given T and δ . By carrying out cuts in the δ - T plane, we were able to determine the type of structures contributing to the SZ effect. In Figure 1, the top panels show the distribution of the mean y as a function of overdensity and temperature. The areas under the curves are the y_{mean} values listed earlier. The bottom panels show the corresponding cumulative mean y fractions, $F_y = y_{\text{mean}}(<\delta)/y_{\text{mean}}$ and $F_y = y_{\text{mean}}(<T)/y_{\text{mean}}$.

The left-hand panels show that the mean y receives contributions from a wide range of overdensities. Cooling reduces the contribution from high-density gas in groups and clusters. Because most of the gas in the simulations is at low overdensity, preheating preferentially raises the contribution from that phase. The right-hand panels in Figure 1 indicate that gas below 10^5 K and above 10^8 K contributes negligibly to y_{mean} . The mean y distributions have similar shapes in the cooling and nonradiative models and are practically uniform in the range $6.2 \leq \log(T/\text{K}) \leq 7.3$ for all runs. Gas above $\sim 2 \times 10^7$ K produces the same amount of distortion independently of the model considered. The preheating run shows a sharp peak at $T \approx 10^6$ K resulting from IGM gas heated to this temperature by the energy injection at $z = 4$. While preheating will indeed insert a new temperature scale, the narrowness of this feature is no doubt an artifact of our simplified method and would be broadened in reality. Indeed, there is evidence that some of the IGM is cooler than this (Schaye et al. 2000).

Figure 2 shows the rms temperature perturbation, σ_{rms} , as a function of beam resolution, θ_{FWHM} , obtained by averaging the 30 thermal (Rayleigh-Jeans band) and kinetic SZ maps. The different cooling/preheating models shift the curves by tens of percent. On the angular scales shown, the kinetic dispersions are a factor of about 5 smaller than the thermal, confirming earlier results using lower resolution simulations (da Silva et al. 2001).

Figure 3 shows the SZ angular power spectra in the Rayleigh-Jeans region, with C_l defined in the usual way. In each case,

⁵ A collection of color images and animations can be viewed at <http://www.astronomy.sussex.ac.uk/users/antonio/sz.html>.

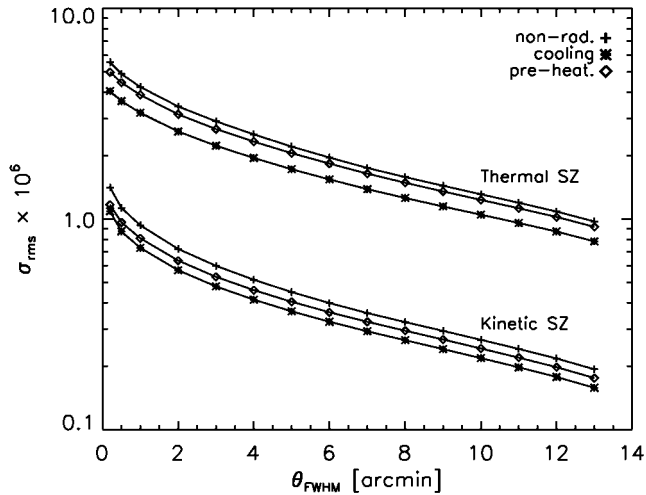


FIG. 2.—Dispersion σ_{rms} for the thermal and kinetic effects as a function of beam resolution (assuming Gaussian beams with $\text{FWHM} = \theta_{\text{FWHM}}$).

the curves show averages over 30 sky realizations, and the error bars are statistical errors at 68% confidence level obtained by bootstrap resampling the set of maps. The map-to-map variations are typically much higher than these, and in particular, as we will see below, the large angular scales are significantly affected by sample variance as well as the finite map size. Comparing the different models, we see that the curves have similar shapes, with the thermal power spectra dominating the kinetic ones on all scales and dominating the primary CMB anisotropies for $l > 3000$. Radiative cooling has the effect of lowering the SZ spectra by a factor of about 2 as compared with the nonradiative case. Our model of preheating raises the spectra again, although only part way back toward those found in the nonradiative run.

Figure 4 shows the contributions to the power spectra from the low-overdensity IGM ($\delta < 100$) and from bound gas in halos ($\delta > 100$). Most of the thermal signal comes from the bound gas, with the IGM contribution an order of magnitude below. The kinetic signal is dominated by halos in the non-radiative run and by the IGM phase in the cooling simulation, and it has roughly equal contributions from each in the pre-heating model. Accordingly, treatments of the kinetic effect that concentrate solely on bound halos are likely to miss much of the kinetic signal. For both the thermal and kinetic effects, the contribution from low-density gas is similar in all three models, and the difference in the spectral amplitudes is therefore due mainly to the contribution of the high-density gas. These differences mainly reflect the different amounts of cooled material in halos in each simulation. At $z = 0$ the amount of cooled material in the preheating run is a factor of about 2 less than in the cooling simulation (while the nonradiative model does not include star formation at all).

We end by discussing how cosmic variance and numerical resolution affects these determinations. Even though our spectra are averages over 30 maps, there remains some sensitivity to rare features, and because these are non-Gaussian they can have large effects, as reflected in the bootstrap errors. One of the 30 thermal maps is dominated by a very nearby bright source, strong enough to greatly boost the estimated power spectrum. In Figure 5 the solid line reproduces the mean power spectrum from Figure 3, while the dashed line shows the median power spectrum, which is close to what would have been obtained had a single map with a bright source by chance not appeared

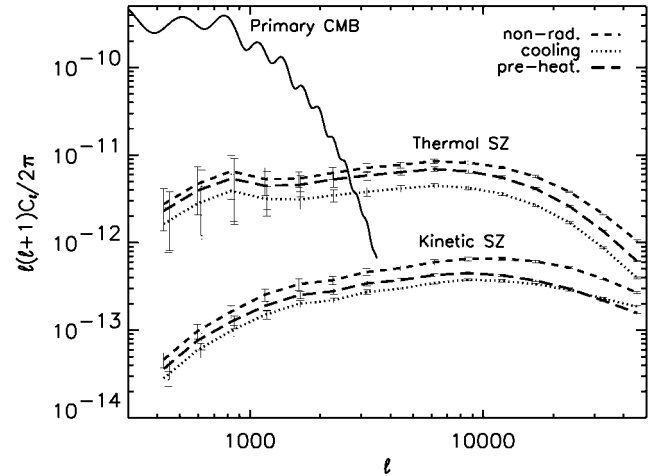


FIG. 3.—Thermal and kinetic angular power spectra from the three simulations. Curves are averages over 30 maps, and bars are 1σ bootstrap errors.

in the set. The median is consistent with the bootstrap errors (which of course include subsamples without that map); note, however, that it is the mean, not the median, that is the maximum likelihood power spectrum estimator. We conclude that there is considerable sample variance error in estimating the thermal power spectrum from observations with limited survey areas. The dotted lines show the SZ power spectra obtained from the nonradiative Λ CDM simulation studied in da Silva et al. (2001), which had a mass resolution 19 times worse than the present simulations. The loss of power due to resolution in the earlier results is clearly seen at high l , an effect particularly severe in the kinetic case, and our new results extend

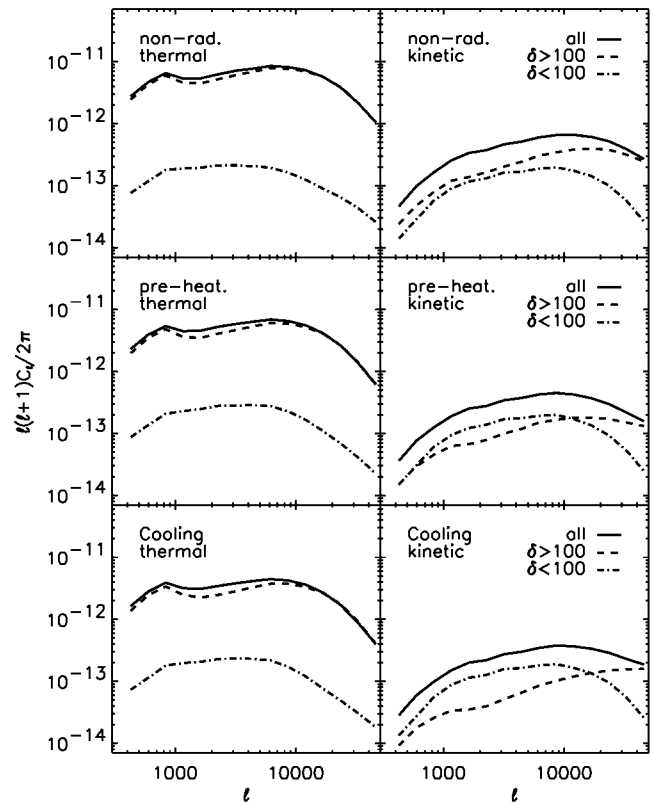


FIG. 4.—Contribution to the spectra from gas in halos ($\delta > 100$) and the low-overdensity IGM ($\delta < 100$).

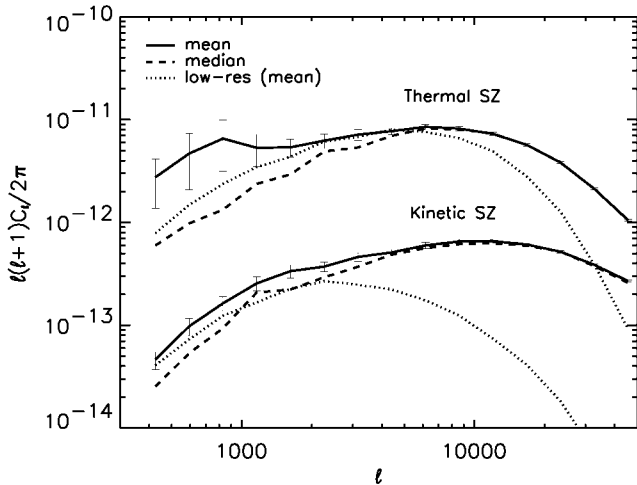


FIG. 5.—Effects of sample variance and resolution on the SZ spectra obtained from nonradiative simulations. The curves are the mean power spectra (solid lines), the median of the C_ℓ distributions (dashed lines), and the mean power spectra from da Silva et al. 2001 (dotted lines).

the l range for which the power spectra are reliably obtained. Based on the demonstrated convergence of the low-resolution simulations, we estimate the thermal power spectrum is accurately determined out to an l of at least 20,000.

Our nonradiative SZ angular power spectra show broad agreement with the results obtained by other authors, who use only nonradiative hydrodynamical simulations. After accounting for the differing σ_8 and $\Omega_b h$, on large scales our mean thermal spectrum agrees well with the results of Refregier et al. (2000) and Refregier & Teyssier (2000), whereas the predictions from Seljak et al. (2001) and Springel et al. (2001) are closer to our median C_ℓ -values. On small scales our mean

thermal spectrum shows somewhat less power and a similar shape to the results in Springel et al. (2001) and Refregier & Teyssier (2000), while our kinetic angular power spectrum is in good agreement with that of Springel et al. (2001).

4. CONCLUSIONS

We have analyzed the impact on the magnitude and spectrum of the SZ effect of physical processes in the hot gas, including both radiative cooling and a crude model for preheating of the IGM. While neither radically alters the appearance of the SZ sky, the details of how the signal is generated are modified. Cooling reduces the angular power spectrum by a factor of around 2 as compared to nonradiative simulations, while our preheating model gives a significant boost to the mean distortion but a more minor change to the power spectra.

We have studied these effects in more detail by classifying the gas into two phases. While the mean thermal distortion receives equal contribution from gas in halos and the IGM, the thermal angular power spectrum is dominated by contributions from hot gravitationally bound gas. By contrast, the kinetic power spectrum receives equal contributions from both phases in the preheating run and is dominated by the IGM in the cooling model. For both the thermal and kinetic SZ spectra, the contribution from IGM gas is similar in all three models, whereas the contribution from gas in halos is largest in the nonradiative simulation and lowest in the cooling run.

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⁶ See <http://www.virgo.sussex.ac.uk>.

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